

# Tunnelling and Swelling in Triassic Sulphate-Bearing Rocks.

## Part I. Case studies from Baden-Württemberg

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### ABSTRACT

Cases of swelling in tunnels excavated through Triassic sulphate-bearing rocks from the Gipskeuper and the Anhydritgruppe are presented and discussed in this series of papers in order to gain a better understanding of the expansive phenomena in these materials and to identify the most relevant ones. Part I deals with main features of swelling in tunnels and alternative supports designs for their control and mitigation, as well as with the phenomenology of swelling in tunnels from Baden-Württemberg (Germany) excavated through the Gipskeuper.

**Keywords:** sulphate-bearing rocks, Gipskeuper, swelling, tunnel, Baden-Württemberg.

### CONSTRUCCIÓN DE TÚNELES Y EXPANSIÓN DE ROCAS TRIÁSICAS SULFATADAS. PARTE I: ESTUDIO DE CASOS DE BADEN WÜRTTEMBERG

### RESUMEN

En esta serie de artículos se presentan y discuten casos de expansiones en túneles excavados a través de rocas Triásicas sulfatadas del Gipskeuper y del Anhydritgruppe con el propósito de adquirir un mejor entendimiento de los fenómenos expansivos en esos materiales e identificar sus aspectos más relevantes. La Parte I trata sobre los principales aspectos de las expansiones en túneles y las alternativas de soporte para su control y mitigación, así como sobre la fenomenología de las expansiones en túneles de Baden-Württemberg (Alemania) excavados a través del Gipskeuper.

**Palabras clave:** rocas sulfatadas, Gipskeuper, expansión, túnel, Baden-Württemberg.

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## INTRODUCTION

The characterization of the main phenomenological aspects of expansions in sulphate-bearing rocks has an enormous importance to identify the mechanisms underlying the swelling, their triggering events and the causes of heave and swelling pressure exhaustion. This series of papers deals with the phenomenology of swelling in tunnels excavated through Triassic anhydritic-gypsiferous claystones from the Anhydritgruppe and the Gipskeuper, in particular with the swelling-time relationships.

Fundamentals of the principles of resisting and yielding support applied to rock swelling affecting tunnels are presented and selected case studies – including tunnels and test galleries, are presented. The theme is tackled covering a spectrum of cases initiating with those located in Baden-Württemberg (Germany) –Part I– and concluding with experiences gained in tunnels from Jura Mountains (Switzerland) –Part II.

In each one of the exposed cases the most important construction and operation aspects are described and their possible effects on rock swelling discussed. Special attention is given to rock-groundwater-environment interaction conditions under which the compiled phenomenology was observed as well as to indicators of chemo-mechanical degradation of implicated rocks.

This work is the result of comprehensive analyses of data on tunneling in Germany and Switzerland that were carried out as a part of the research project “Anhydritic Claystones and their Impact on Public Works”, developed by the consortium CIMNE-Department of Geotechnical Engineering and Geosciences (UPC) with the financial support of the Spanish Ministry for Infrastructures.

## SWELLING IN TUNNELS AND ALTERNATIVE SUPPORT DESIGNS

### SWELLING AFFECTING TUNNELS

The deleterious effects of rock swelling on excavations in general and tunnels in particular, have been demonstrated –even better than in any other cases–, in those cases in which sulphate-bearing rocks (namely, SBR) are involved. Generally the magnitude of expansive phenomena observed in these materials far exceeds the expansive potential of most hard soils and rocks, which is the reason for their notoriety. In figure 1 several cases of both underground and shallow excavations in swelling rocks and soils are presented, and the division between SBR and other expansive materials facilitates a first assessment of the magnitude of phenomena studied in this paper.

Figure 1 points out that under similar conditions of construction and operation of tunnels heave and swelling pressures in SBR could be up to one order in magnitude greater than in expansive clayey materials. These observations have been unequivocally confirmed in some tunnels from Jura Mountains, to be precise in Hauenstein, Bözberg and Belchen.

Incidents affecting tunnels in expansive rocks are certainly well identified: swelling –and in extreme cases the failure of structural elements–, appear preferentially at floor level without appreciable damage in abutments and crown. Depending on excavation geometry, lining rigidity and overburden stiffness either vertical displacements or pressures can make possible the occurrence of one or a combination of events presented in figure 2.

Due to the intrinsic heterogeneity of SBR the casuistry of swelling effects on tunnels integrity is often broad and complex: heave and pressures occur in a highly disperse form along both the longitudinal and

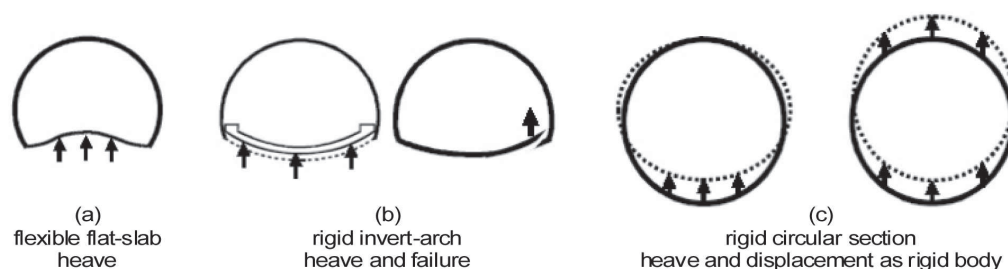
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**Figure 1. Field observations of extreme expansive phenomena in tunnels, caverns, deep excavations and foundations in swelling rocks and soils.**



(A) Krause (1976), (B) Amstad & Kovári (2001), (C) Einstein (1979), (D) Krause & Wurm (1975), (E) Grob (1972), (F) Nagel (1986), (G) Grob (1976), (H) Wittke-Gattermann (1998), (I) Paul & Wichter (1996), (J) Alonso et al. (2004), (K) Berdugo et al. (2006), (L) Bischoff & Hagmann (1977), (M) Dhowian (1984), (N) Young (2004), (O) Abduljauwad et al. (1998), (P) Steiner (1993), (Q) Huder & Amberg (1970), (R) Wichter (1985), (S) Wittke (2000), (T) Fecker (1992), (U) Noher et al. (2006).

**Figure 2. Typical events associated with swelling in tunnels according to Amstad & Kovári (2001).**



the transversal alignments. Then, a single optimized cross-section for design and construction could hardly be formulated and longitudinal reinforcement of the structure is often necessary.

Damage and failure due to expansive phenomena in tunnels excavated through Triassic hard SBR from both the Middle Keuper (Gipskeuper) and the Muschelkalk (Anhydritgruppe) in Baden-Württemberg (Germany) and Jura Mountains (Switzerland) have been analyzed by many authors during decades. The works of Kovári & Descoeurdes (2001), Amstad & Kovári (2001), Wittke (2000) and Wittke (2006) nowadays –in the same way than the works of Sahores (1962), Kaiser & Wichter (1975), Kaiser (1976, 1977, 1978), Henke (1976), Kaiser (1976), Krause (1976), Einstein (1979), Wichter (1985, 1991), Nagel (1986), Fecker (1992), Steiner (1993), Paul & Wichter (1996) and others in the recent past–, stand out from other contributions in the study of swelling in hard anhydritic-gypsiferous clayey rocks.

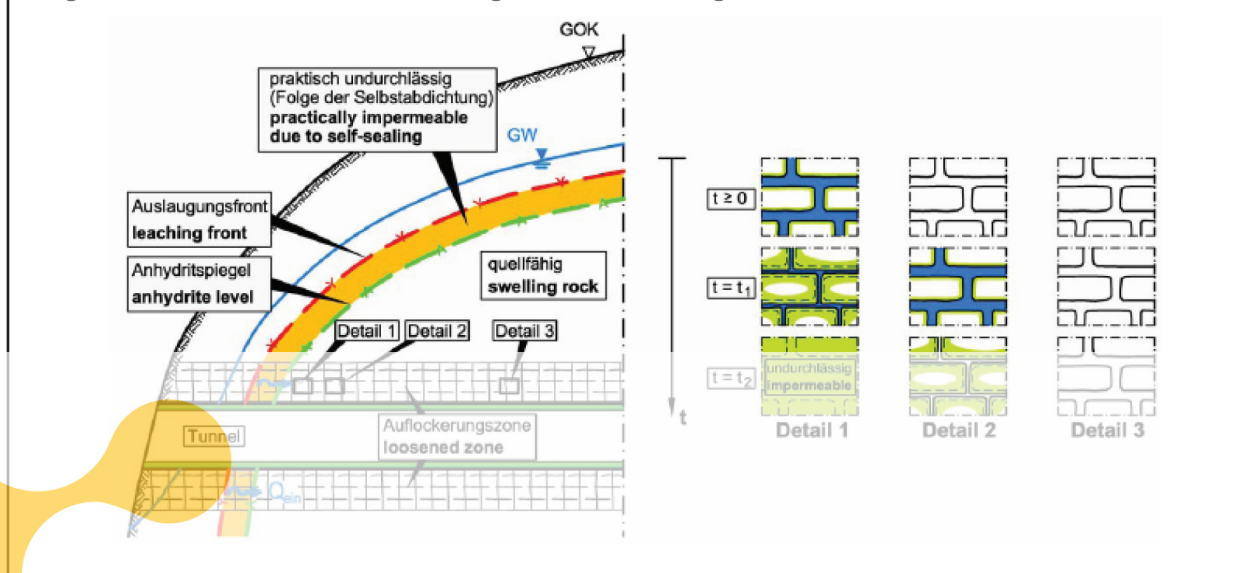
### RESISTING AND YIELDING SUPPORT

Tunnels excavated through swelling rocks and soils are often designed according to the principle of resisting support, which consists in design the lining to resist the occurring swelling pressure. According to Wittke and co-workers at WBI Ltd., optimization of resisting support design for tunnels in SBR is possible if self-sealing due to swelling above the tunnel crown is properly taken into account.

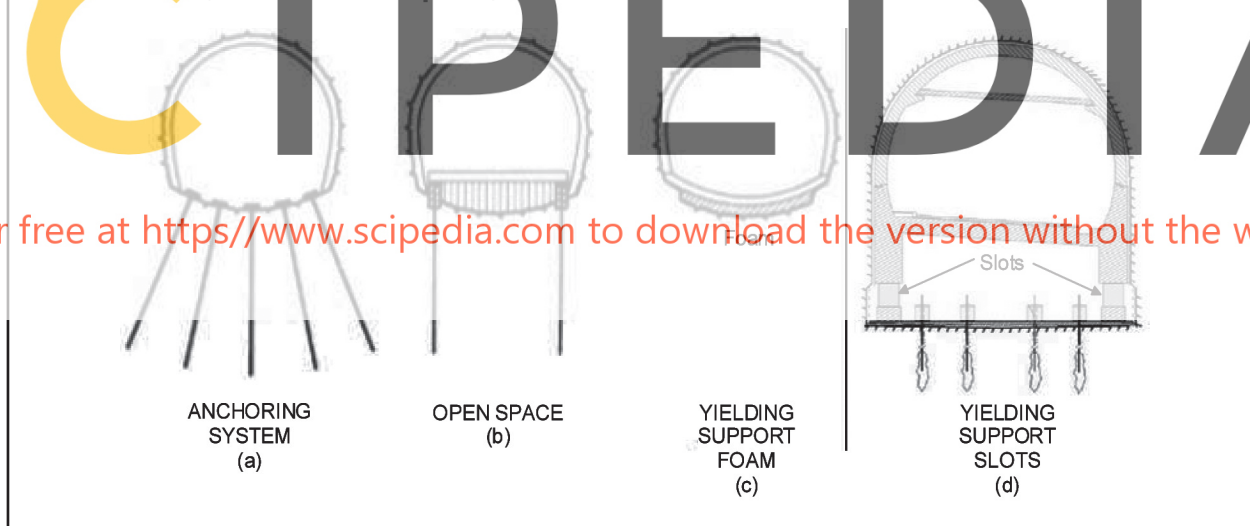
Self-sealing is a mechanism linked, among other causes–, to crystal growth in porous media, which in the case of SBR concerns to gypsum growth in either relict or induced discontinuities. Following Wittke–Gattermann & Wittke (2004) and Wittke (2006): “[...] in the area of the transition from water bearing to anhydritic rock, self-sealing due to swelling occurs around the tunnel if the resisting principle is applied. As a consequence of this self-sealing effect seepage through the rock parallel to the tunnel and thus also swelling is interrupted at a certain distance from the water bearing formation”. According with these authors, a limit value for swelling pressure can be defined, which allows self-sealing and thus the thickness and the reinforcement of the lining considerably reduced. The mechanisms of self-sealing proposed by Wittke–Gattermann & Wittke (2004) is illustrated in figure 3.

The self-sealing criterion postulated by Wittke and co-workers defines an effective limit for the active zone above the tunnel crown (see figure 3). However, it could be precisely defined only if a detailed hydrogeological model of the rock massif is available. On other hand, in the self-sealing approach by Wittke–Gattermann & Wittke (2004) the role played by the chemical composition of groundwater and the relative humidity induced by the natural tunnel ventilation is not considered and the mechanisms for gypsum crystallization is not explicitly defined.

**Figure 3. Mechanisms of self-sealing in SBR according to Wittke (2006).**



**Figure 4. Alternative support designs for tunnelling in swelling rocks (Kovári et al., 1988 and Solexperts, 2007)**



The permanent damage and failure of invert designs according to the principle of resisting support leads to study other support alternatives to handle the swelling phenomena in rocks by other means than just trying to withstand the pressure by heavy and very strong linings. These alternatives included, mainly, the use of anchored plates and yielding support systems (see figure 4). In yielding support systems the design criterion consists in finding the best

possible equilibrium between swelling deformations and pressures in order to limit both the deformation of the structure and the swelling pressure of the rock against the lining. Two alternatives of yielding support systems can be used to reduce radial pressures due to swelling: foam and slots.

The classic yielding support alternative is the installation of a deformable zone —usually foam—, be-



neath the invert of the tunnel (figure 4c), combined with drainage of the yielding zone to prevent groundwater from reaching the rock above the tunnel roof and thus to prevent swelling of the rock in this area (Wittke–Gattermann & Wittke, 2004). In general, the deformable (yielding) zone leads to a significant reduction of the thickness and the reinforcement of the tunnel lining.

The principle of yielding support using foam to compensate the effect of the swelling capabilities of clayey rock masses was used for the first time in the middle 70's in Buechberg highway tunnel —Eastern Switzerland—, and afterwards in the tunnel for the Super Proton Synchrotron at C.E.R.N. —Geneve—, (Lombardi, 1979) and Tunnel T8 Biel–Sonceboz —Switzerland—, (Kovári et al. 1988). In spite of the noticeable benefits related to the use of this system in clayey swelling rocks experiences in tunnels through SBR are limited to the cases of Gastollen Cogefar —Italy—, (Amstad & Kovári, 2001), Freudenstein test gallery —Germany—, (Kirschke, 1987; Prommesberger & Kuhnheim, 1989; Fecker, 1992), Freudenstein tunnel (Kovári & Amstad, 1993; Amstad & Kovári, 2001) and Engberg base tunnel (Amstad & Kovári, 2001).

Recently comprehensive studies on applicability of both resisting and yielding supports (foam) for tunnelling in the project Stuttgart 21, including numerical modelling, have been published by Wittke & Wittke (2005) and Wittke (2006). For these authors the key factors in the selection between the two support alternatives for tunnelling in SBR are the amount of weathering of the overburden and the location of the water table, as follows:

1. If the tunnel is well covered with competent materials and water is only available underneath the invert of the tunnel, the invert is subjected

to higher bending in case of a resisting support than in case of a yielding support, but heave cannot be observed in both support systems. The high loading of the shoulders of concrete for the yielding principle is remarkable, leading to high shear forces in the corresponding area of the inner lining. Nevertheless, the bending moments and normal thrust in the internal lining are lower for the yielding principle than for the resisting principle.

2. If degraded material and water are located above the roof, tunnels constructed according with the resisting principle are subjected to heave. Due to the low shear strength and Young's modulus, the overburden provides only small resistance against swelling pressures. Thus, in this case the load of the internal lining due to swelling is comparatively small. Also the difference between the radial loadings on both linings is comparatively small. However, the heaving of the tunnel and the ground above are much smaller in case the yielding principle is used.

According to these authors resisting support is convenient when unweathered materials are located above the tunnel crown; whereas foam is the most convenient alternative in opposite cases.

The second alternative of yielding support is the use of either concrete or steel slots (modular yielding support) in the interface vault–invert, as is illustrated in figure 4d and figure 5. It is certainly a novel alternative; unfortunately, information on the performance of slots in tunnels is really limited. Documented experiences are limited to Chienberg tunnel in Jura Mountains (Thut et al., 2007) —reinforced using high deformable concrete modules (Solexperts HDC®)—, and Lilla tunnel in the Lower Ebro Basin (Berdugo, 2007) —reinforced using steel slots—.

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**Figure 5. Modular yielding supports (slots) installed in the interface vault-invert of tunnels excavated through swelling rocks.**



(a) Highly deformable concrete slots (Solexperts HDC®) in Chienberg tunnel (Jura Mountains).



(b) Metallic slots in a test section of Lilla tunnel (Lower Ebro Basin)

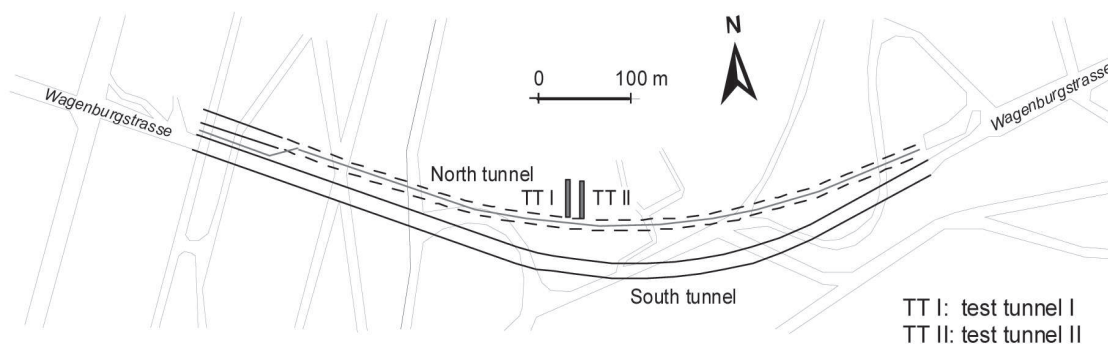
## CASE STUDIES FROM BADEN-WÜRTTEMBERG WAGENBURG TUNNEL

The Wagenburg tunnel connects the centre with the eastern part of Stuttgart. Three independent structures must be distinguished in this case, each one characterized by particular cross sections, but affected by similar expansive phenomena (see figure 6):

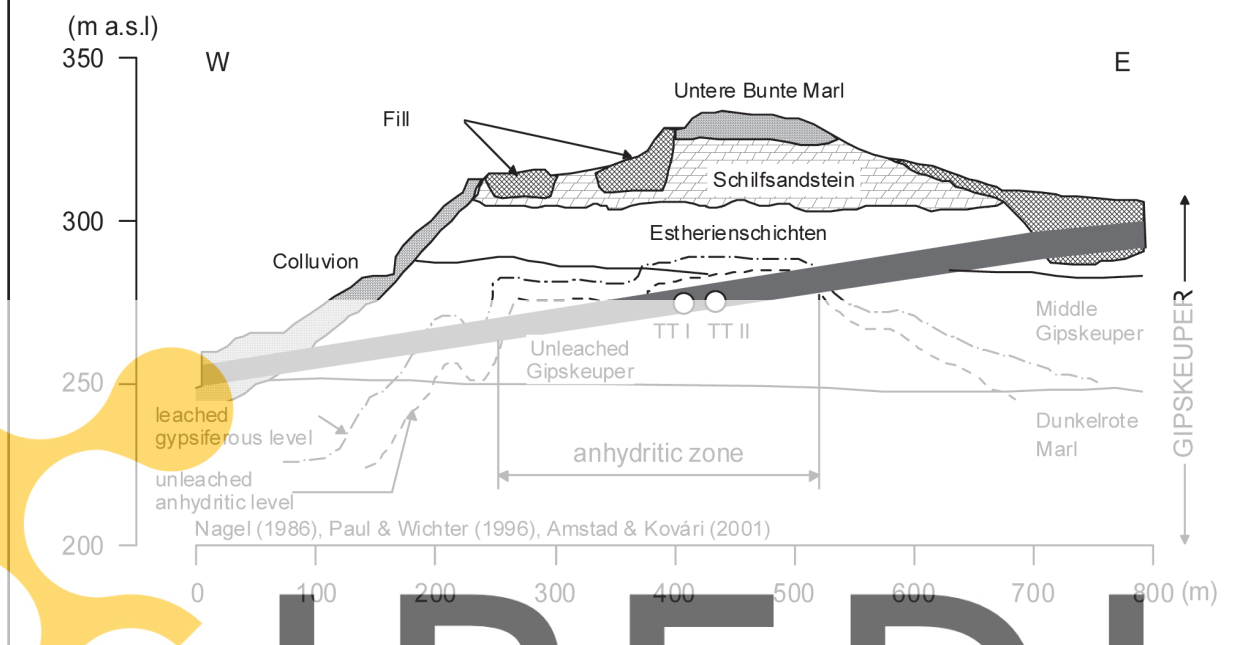
(i) the north tunnel, (ii) the south tunnel, and (iii) the test tunnels. These structures are located mainly within the Middle Gipskeuper and strong swelling is restricted to the innermost 250 m, just in the zone in which the tunnels cross the transition from the leached gypsiferous level to the unleached anhydritic level (see figure 7). Unfortunately, information on the hydrogeological regime in the rock massif is unknown.

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**Figure 6. Localization of structures in Wagenburg tunnel system.**



**Figure 7. Geological longitudinal section of Wagenburg tunnel system.**



#### WAGENBURG NORTH TUNNEL

The north tunnel has a length of 800 m and was completed in 1942. It has a horseshoe cross-section and a concrete lining that covers only the roof and walls, but the floor was unlined and has remained in this state ever since construction (Götz, 1972). Under these conditions the foundation material was exposed to three important weathering agents: (i) the stress relief due to excavation, (ii) the flow of water from overburden, and (iii) the changes in relative humidity imposed by local environmental conditions into the tube.

Expansive phenomena affecting the north tunnel since 1943 until 1970 were described in detail by several authors (i. e. Götz, 1972; Krause, 1976 and Nagel, 1986). The evolution of floor heave in this tunnel was analyzed for this paper using original data by Krause (1976) and Nagel (1986), and is presented in figure 8. After twenty seven years of monitoring, a maximum floor heave of 1029 mm was measured in

the axis of the section and, in general, no asymptotic trends were observed in any of the control stations (see figure 8c).

Weathering and gypsum growth induced swelling certainly affected the foundation material in Wagenburg north tunnel, as illustrated in figure 9. Krause (1976) reported that “[...] inspections of foundation materials in Wagenburg during the early 70’s –and also in Kappellesberg tunnel–, have show that the original anhydrite was converted almost completely to gypsum in the heaving floors without showing any visible increase in volume. Except for strongly leached sections, the sulphate rocks have remained essentially compact”.

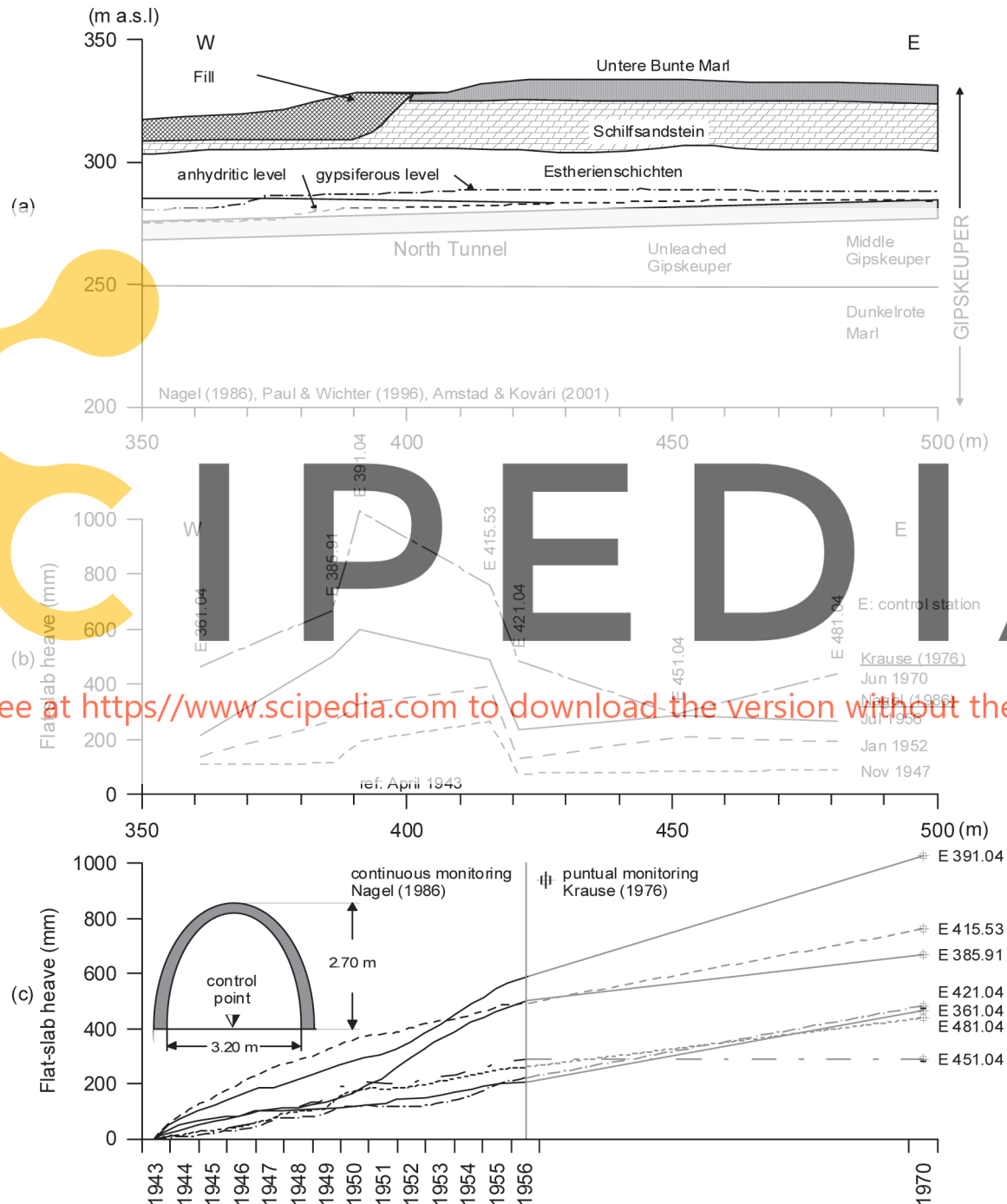
#### WAGENBURG SOUTH TUNNEL

The Wagenburg south road tunnel was constructed parallel to the north tube in the period 1951–1957 and has a length of 824 m. During excavation of the calotte section the foundation material was exposed

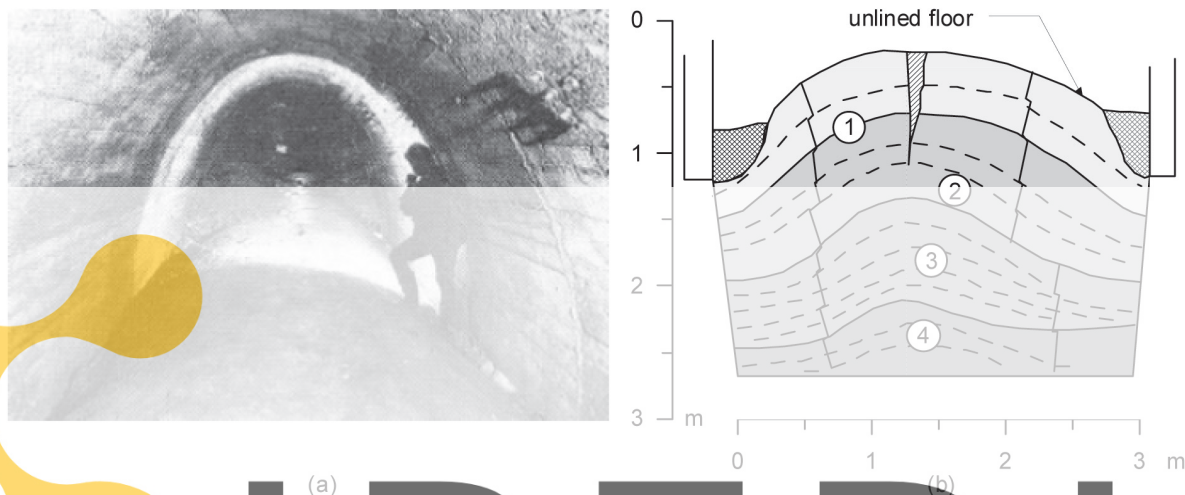
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**Figure 8. Geology and total floor heave in Wagenburg north tunnel after 27 years of monitoring (modified after Krause, 1976 and Nagel, 1986).**



**Figure 9. (a) Wagenburg north tunnel in 1970 in an image by Spaun (1974). (b) Distribution of gypsum crystals along the weathered subsoil profile according to Krause (1977) & Nagel (1986): (1) segregate-impure gypsum crystals and macrocrystals, (2) segregate-pure gypsum crystals in fine sheets, (3) gypsum macrocrystals and fibrous gypsum, (4) transition between (1) and (2).**

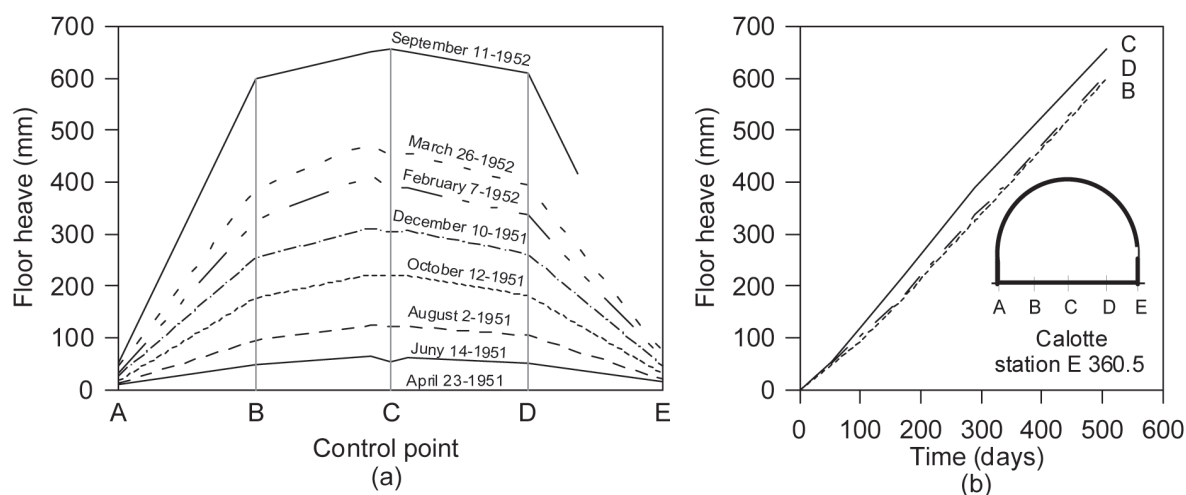


to the environmental conditions imposed by the natural ventilation because the floor was not protected with a concrete lining – just as in the north tunnel–. Vertical displacements of the floor at station E 360

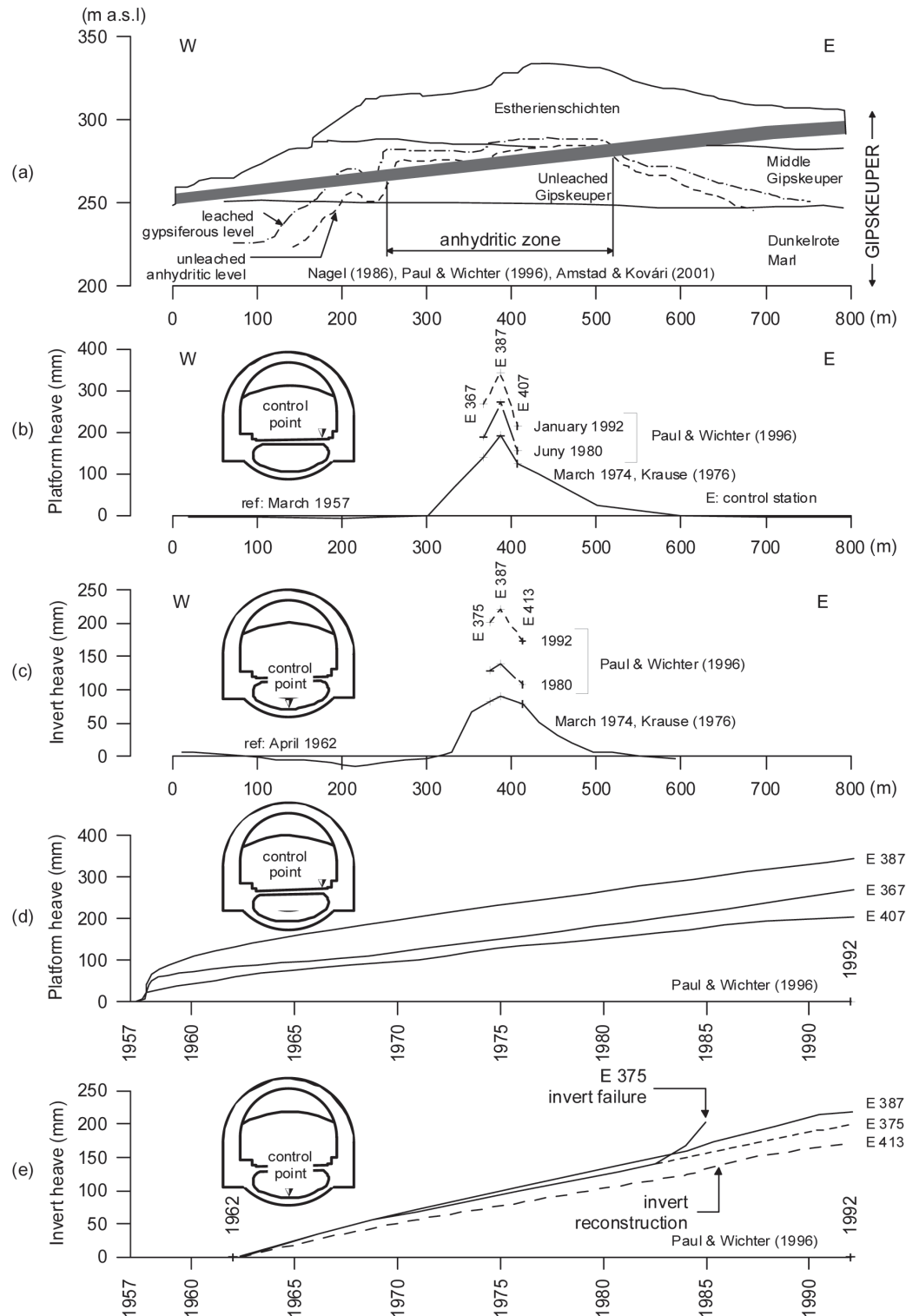
ferous level to the anhydritic level–, were monitored between April 1951 and September 1952 (see figure 10). In the course of seventeen months a maximum floor heave of 659 mm was measured in the section

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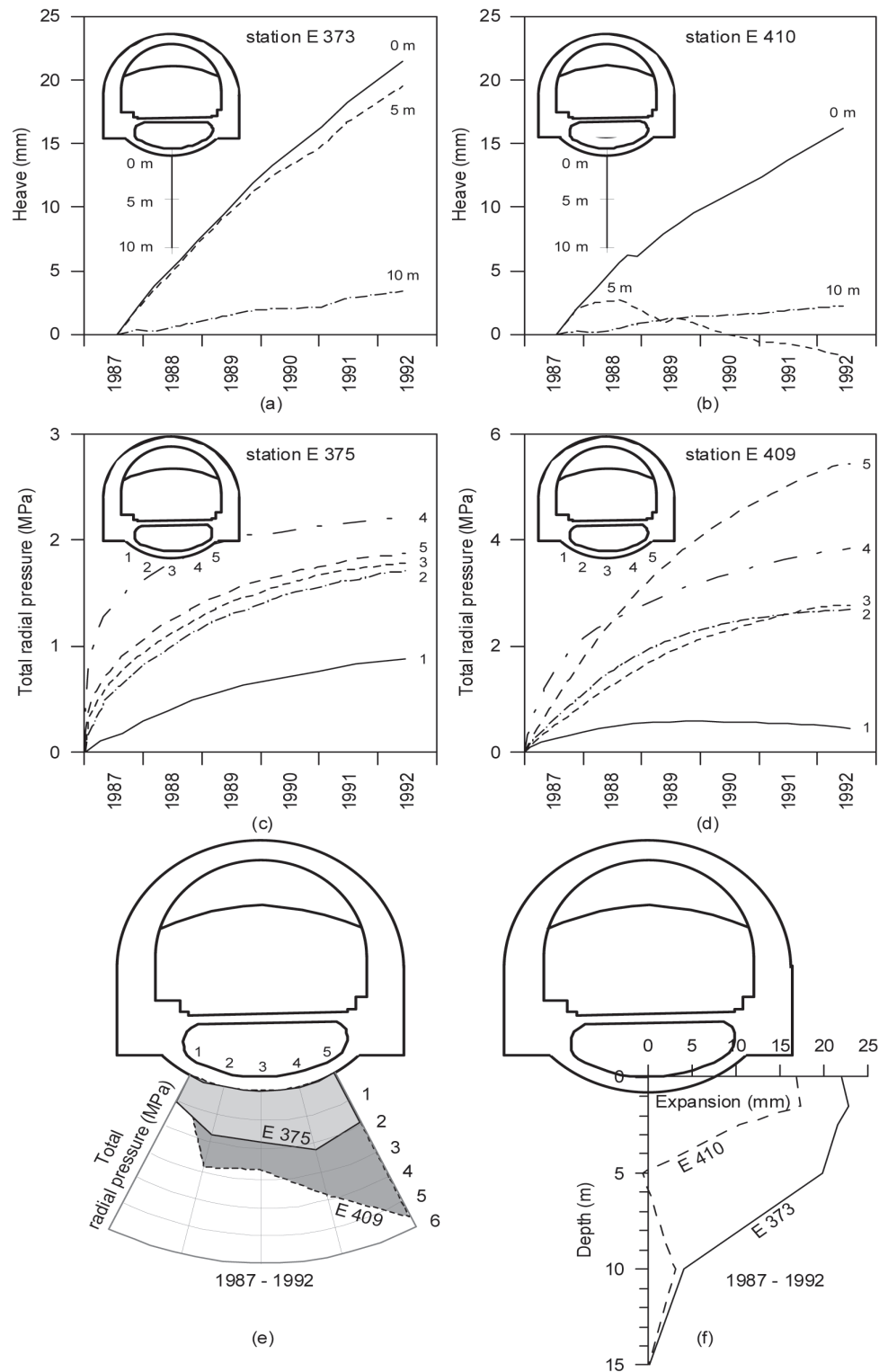
**Figure 10. Floor heave in section E 360 of the south tunnel of Wagenburg during excavation (after Krause & Wurm, 1975). (a) Heave of the cross-section. (b) Evolution of heave around the axis.**



**Figure 11. Heave at platform and invert levels of the resisting support in Wagenburg-south tunnel during operation (modified after Krause, 1976 and Paul & Wichter, 1996).**



**Figure 12. Heave, swelling pressure and active zone in sections of Wagenburg-south reconstructed in 1986 (Paul & Wichter, 1996; Paul & Walter, 2004).**



Important expansive phenomena also affected the rigid invert during operation of the south tunnel, all of them located in the innermost transition from the leached gypsiferous level to the unleached anhydritic level. Complete studies of these phenomena are presented in Götz (1972), Krause (1976), Paul & Wichter (1996) and Paul & Walter (2004).

Since 1957 until 1992 the road surface (platform) showed a maximum increase in elevation of 342 mm in station E 387. On the other hand, measurements of the invert heave initiate in 1962 showed vertical displacements up to 218 mm after thirty years of monitoring in the same station (figure 11). In both cases non-asymptotic heave-time relationships were observed.

In 1986, during a series of reparations in sections affected by failures of inverts, some stations of the south tunnel were instrumented by means of extensometers and load cells. Data from these devices revealed that swelling pressure and heave were re-activated as a result of the reparation works, which generated a new exposition of the foundation material to the relative humidity imposed by the natural ventilation of the tunnel. The evolution and the distribution of swelling in two instrumented stations, as well as the magnitude and the evolution of the active zone in time, are presented in figure 12.

Figure 12e illustrates a characteristic aspect of expansive phenomena in SBR: the heterogeneous distribution of swelling pressure in both the transversal and the longitudinal direction of tunnel inverts. This situation is responsible of high stresses into the concrete and, in extreme cases, causes local failures in the lining, such as the failures observed in the south tunnel before 1986.

Zones near construction joints distributed in a regular form along the longitudinal section of the south tunnel were particularly affected by swelling, as menti-

oned by Paul & Wichter (1996). For these authors the role of construction joints was only related with the possibility of water exchange between the tunnel and the rock. Actually, construction joints connect the environment into the tunnel with the foundation material and act as effective source-sink for both the water and the vapour mass, independently on the general tunnel seal when it is locally damaged.

### WAGENBURG TEST TUNNELS

Large scale in situ tests were carried out in two test tunnels build from the wall of the north tunnel and they were excavated below the anhydritic level of the geological profile of Wagenburg.

The test tunnels, 20 m long, were constructed between 1970 and 1971 adopting a horseshoe cross-section. Roofs and walls were lined with unreinforced shotcrete, but the flat floor was only protected in a zone of the test tunnel II, where an anchored concrete slab was constructed. Both the geometry and the instrumentation of the test tunnels are presented in figure 13.

The test tunnel I was kept free of artificial water supply, whereas the floor of the test tunnel II was kept wet by watering once a week (Henke, 1976; Wichter, 1985, Nagel, 1986). Unfortunately, geochemical properties of the water used during wetting are not reported in the technical literature related with the case. A summary of the observations in the test tunnels of Wagenburg is presented in figure 14.

Low displacements observed in test tunnel I are, at least, apparently consistent with the swelling pressure measured beneath the abutment (3.4 MPa), the highest value obtained during the monitoring of the test tunnels. In spite of the similar conditions imposed to both the north and the test tunnel I, vertical displacements of only 25 mm were measured in the latter after two years of monitoring since 1973. This

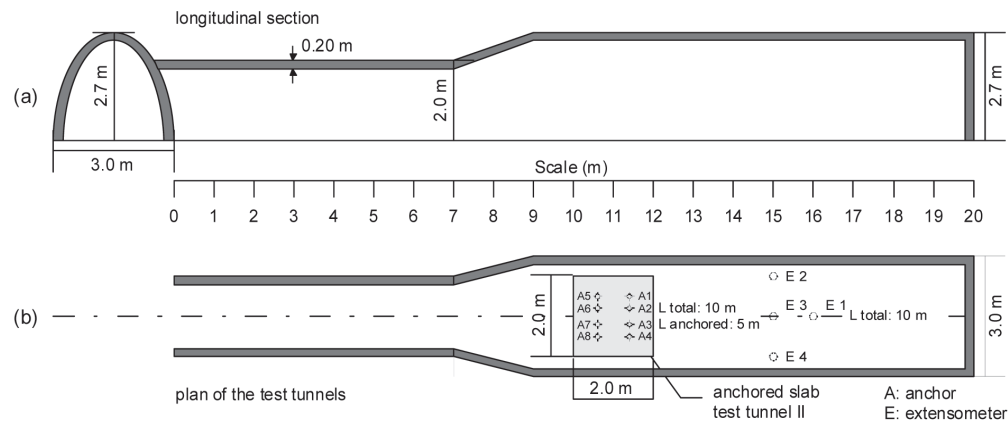


contradictory result has been attributed by Wittke & Pierau (1979) to the absence of ventilation, which leads to high levels of relative humidity into the test tunnel I.

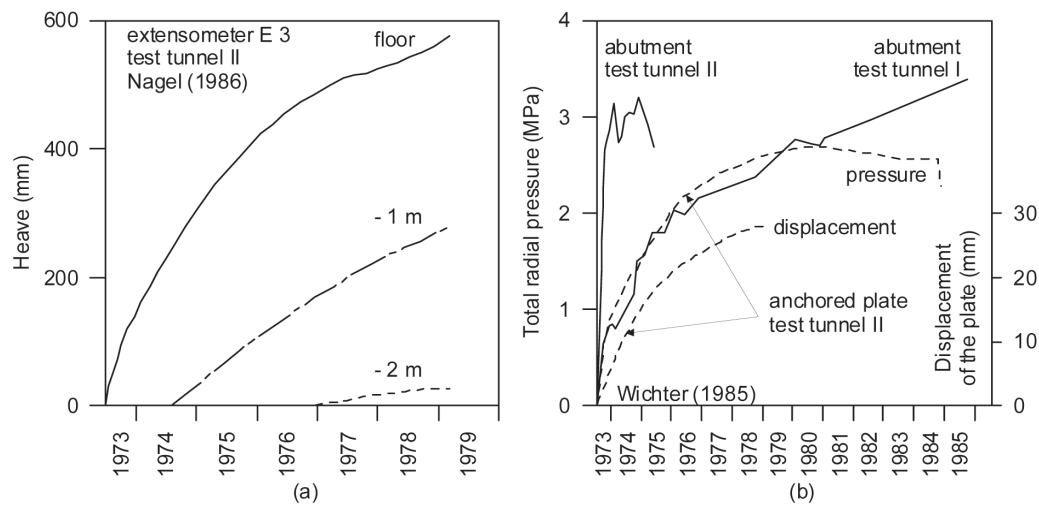
In test tunnel II vertical displacements of the foundation material evolved without a clear limit during the monitoring program. A maximum heave close to 575 mm was observed in the tunnel floor after 6 years of measurements (see figure 14a).

The swelling pressure beneath the abutment of test tunnel II showed a rapid increase up to 3 MPa during the first two years (figure 14b), but a notorious decline was recorded when the cells were destroyed by the major deformations of the floor, during which the abutments were drawn into the test tunnel. Finally, the anchor forces rose as a result of the heaving of the foundation material beneath the concrete plate and reached a value of 2.8 MPa after seven years of monitoring since 1973; then the pressure decreased slightly until the failure of three bolts in 1984 (Wichter, 1985).

**Figure 13. Test tunnels I and II in Wagenburg tunnel system (modified after Henke, 1976; Wichter, 1985 and Nagel, 1986). (a) Longitudinal section and (b) Plan view.**



**Figure 14. Summary of observations in Wagenburg test tunnels.**

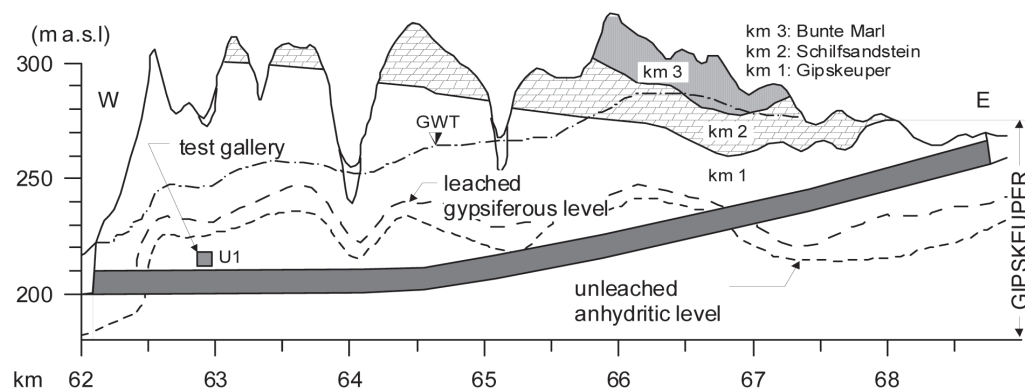


### FREUDENSTEIN TEST GALLERY

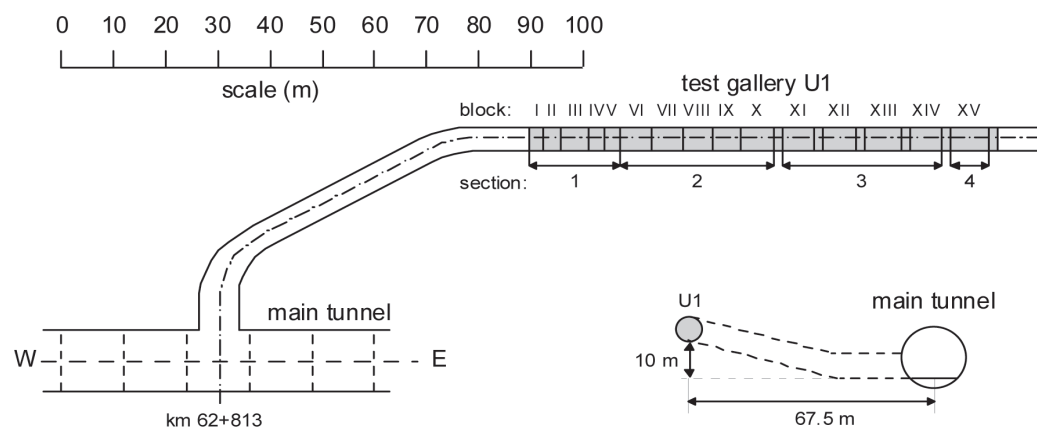
The Freudenstein tunnel has a length of 6.8 km and is located in the high speed railway line Mannheim–Stuttgart. The tunnel traverses the Gipskeuper, including unfractured–unleached sulphate rocks containing layers of anhydrite and clay with high swelling potential in the first 4.1 km. In the eastern zone the material is the strongly leached Gipskeuper consisting in alternating layers of water-bearing and variably weakened rocks (Kovári & Amstad, 1993). As in Wagenburg tunnel, the leached and the unleached strata are separated by the gypsiferous level. The phreatic surface in the formation is about 60 m over the main tunnel. These geological details are presented in figure 15.

In the chainage 62+813 of Freudenstein tunnel a test gallery parallel to the main tunnel, located within the unleached Gipskeuper, was constructed in the 80's to try out different design concepts in the swelling sulphate-bearing rock, including both resisting support and yielding support (Kirschke, 1987; Prommersberger & Kuhnhehn, 1989; Wittke, 2000). The test sections in the test gallery have half the size of those in the main tunnel and are divided into four sections and fifteen blocks, each of one with a different shape and thickness of lining, designed with a different support criterion. The characteristics of the test gallery were described in detail by Fecker (1992) and Wittke (2000) and are summarized in figure 16 and figure 17.

**Figure 15. Geological longitudinal section of Freudenstein tunnel (modified after Kirschke, 1987).**

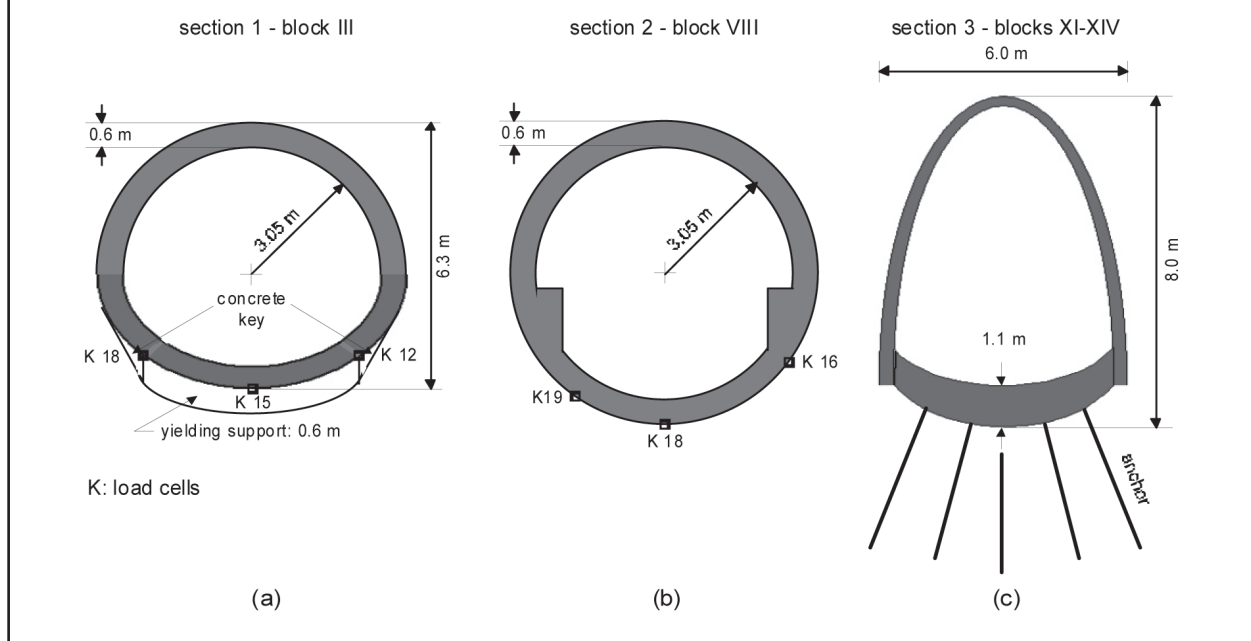


**Figure 16. Test gallery U1 of Freudenstein tunnel (modified after Fecker, 1992 and Wittke,**



2000).

**Figure 17. Characteristics of tests sections in Test gallery U1 of Freudenstein tunnel (modified**



**after Wittke, 2000).**

All test sections in the gallery were instrumented by means of extensometers and load cells. The rock swelling was artificially initiated since 1987 by means of an extensive watering system. As in test tunnels of Wagenburg, geochemical properties of the water used during wetting of Freudenstein tests gallery are not reported in the technical literature related with the case.

Section 1 was constructed according to the principle of yielding support and a deformable zone (foam) was placed underneath the invert (figure 17a). The yielding support allowed large swelling strains and therefore reduced the total radial pressure acting on the section (figure 18). Section 2 was constructed according to the principle of resisting support with an internal lining of reinforced concrete able to resist the swelling pressure under low strain conditions (figure 17b). The effect of the support rigidity on the magnitude of expansive phenomena is evident when

yielding and resisting supports used in Sections 1 and 2 are compared (see figures 18 and 19). However, in both cases heave and total radial pressures evolved without a clearly asymptotic tendency. In blocks XI to XIV of Section 3 anchorages were installed in order to impose approximately constant stresses underneath the invert of 0.75, 0.5, 0.25 and 0.1 MPa by means of a controlled release of anchor forces (figure 17c). In all cases expansions under constant load evolved systematically without signs of stabilization (figure 20).

At first sight, data from the test gallery of Freudenstein tunnel do not add relevant information and they confirm the lessons learned from Wagenburg tunnel with regard to both the magnitude and the evolution of expansive phenomena in SBR. However, two important aspects should be highlighted.

- i. A yielding support certainly reduces the magnitude of total radial pressure, but is not guarantee

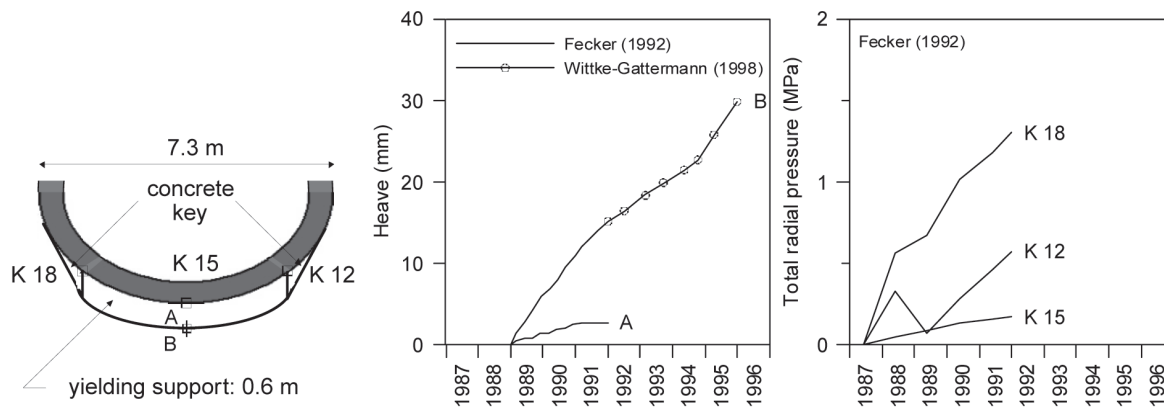
for its long-term stabilization and involves the occurrence of important and continuous vertical displacements (see figure 18).

ii. The extent of the active zone seems to be not

affected significantly by the shape of excavation and remained relatively constant since the beginning of the induced swelling (see figures 19 and 20). Consequently, it is reasonable to assume that weathering of the foundation material is also li-

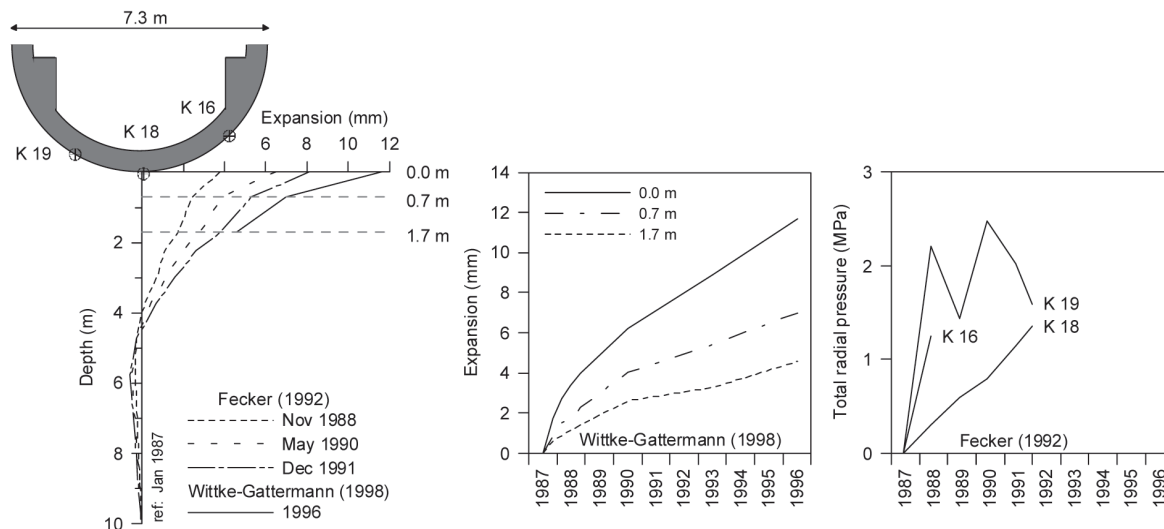
mitted to a relatively well defined thickness.

**Figure 18. Swelling phenomena in block III of section 1 constructed with a yielding support. Test**



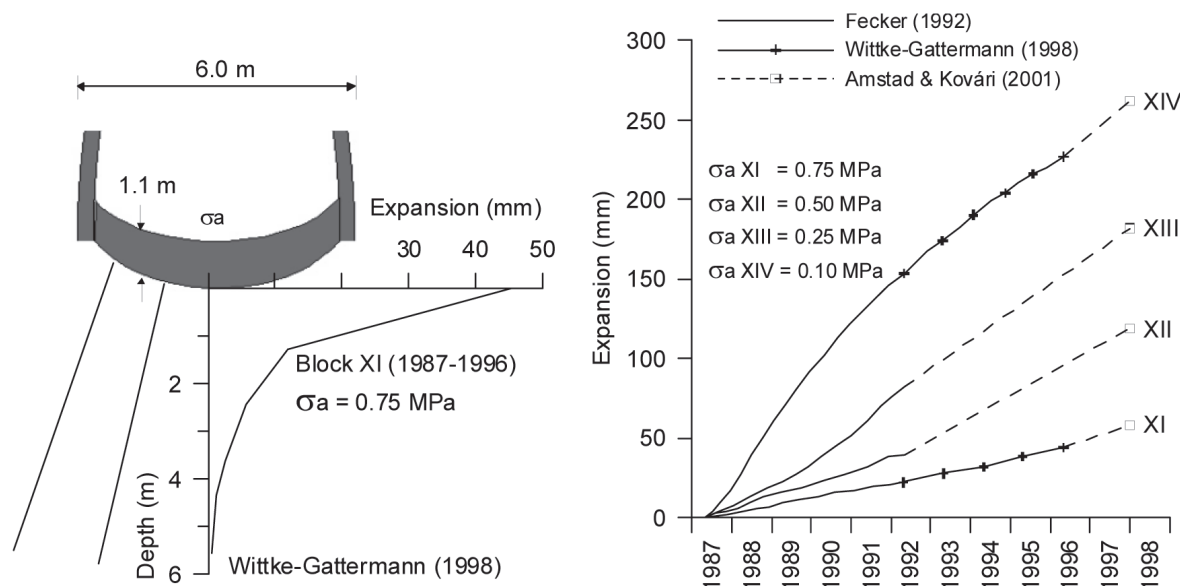
**Gallery U1 of Freudenstein tunnel.**

**Figure 19. Swelling phenomena in block VIII of Section 2 constructed with a resisting support.**



# Test Gallery U1 of Freudenstein tunnel.

**Figure 20. Swelling phenomena in blocks XI–XIV of Section 3 constructed with a resisting support**



consisting in an anchored invert. Test Gallery U1 of Freudenstein tunnel.

## HESLACH II TUNNEL

Interesting information on swelling in the Middle Gipskeuper has been obtained from observations in Heschach II tunnel in Stuttgart. Meticulous in situ swelling tests were executed between 1987 and 1988 in the middle section of the alignment –just in a zone in which the tunnel is located in the transition from the leached gypsiferous level to the unleached anhydritic level (see figure 21a)–. The results obtained were used to optimize the design of the definitive lining of the tunnel, which consisted in a circular resisting support with an excavated diameter of 12.4 m and a 1.8 m thick invert (Wittke, 2006).

Complete details of in situ tests in shaft 2 of Heschach are presented in (Wittke, 2000), and are summarized as follows. The shaft 2 was 7.35 m deep and it was excavated from the invert of the test gallery; so that

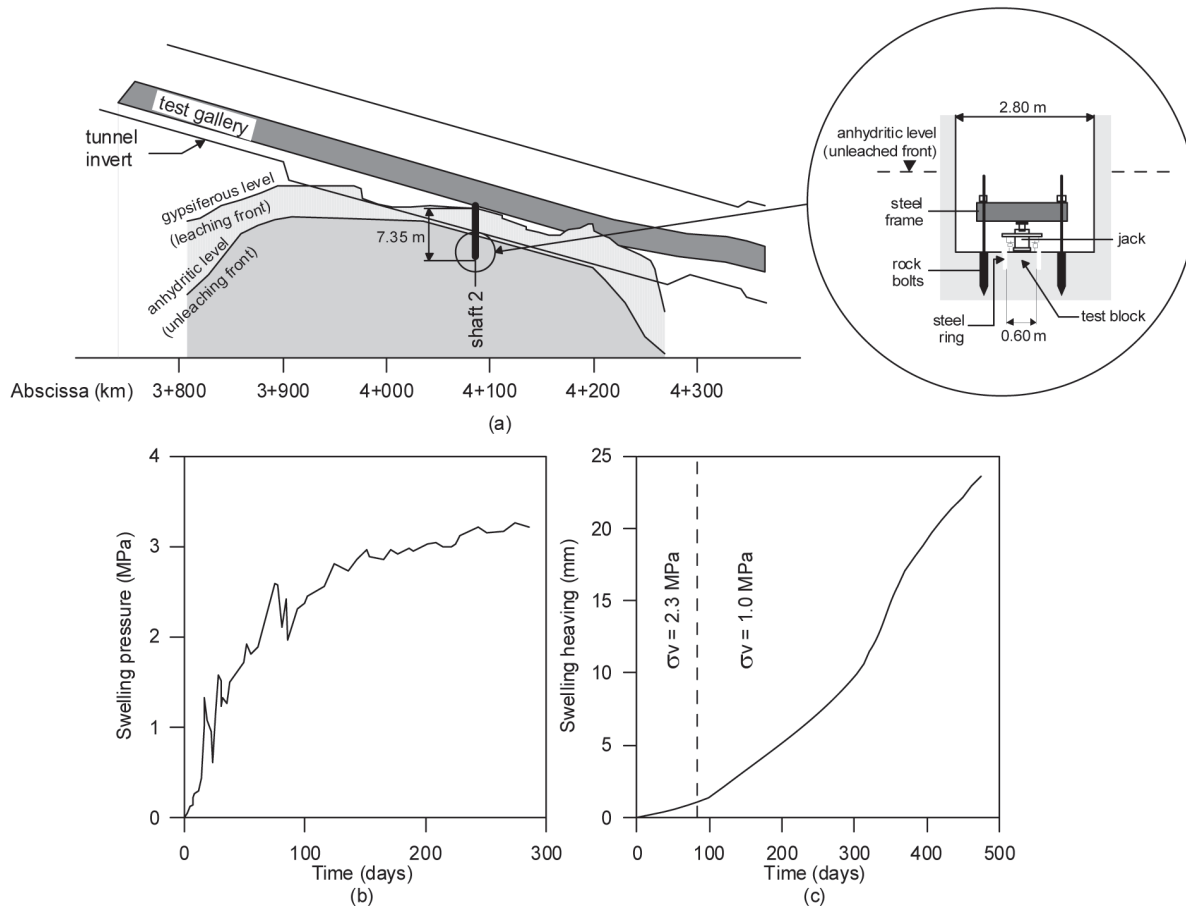
the bottom was located 2 m below the anhydritic level (see detail in figure 21a). At the shaft's bottom two circular gaps with a diameter of 600 mm each were drilled and steel rings placed to make up a full-scale oedometer block. It was loaded vertically using a rigid system consisting in a jack, a thrust plate and a steel frame anchored to the rock.

Two consecutive swelling tests were executed on the block in shaft 2. The first was a swelling pressure test in which the force necessary to prevent heave at the block upper surface was measured as a function of time. The second was a swelling under load test performed in two stages with axial pressures of 2.3 and 1.0 MPa, respectively. In both tests the block was watered in order to accelerate the rock expansive response; however, the chemical composition of the water is unknown.

Both the swelling pressure and swelling heaving evolution in time measured in these in situ oedometer



**Figure 21. (a) Geological longitudinal profile of the test zone in Heselach II tunnel and a detail of the in situ test assembly. (b) Results of the in situ swelling pressure test. (c) Results of the in situ swelling under load test (Wittke, 2000).**

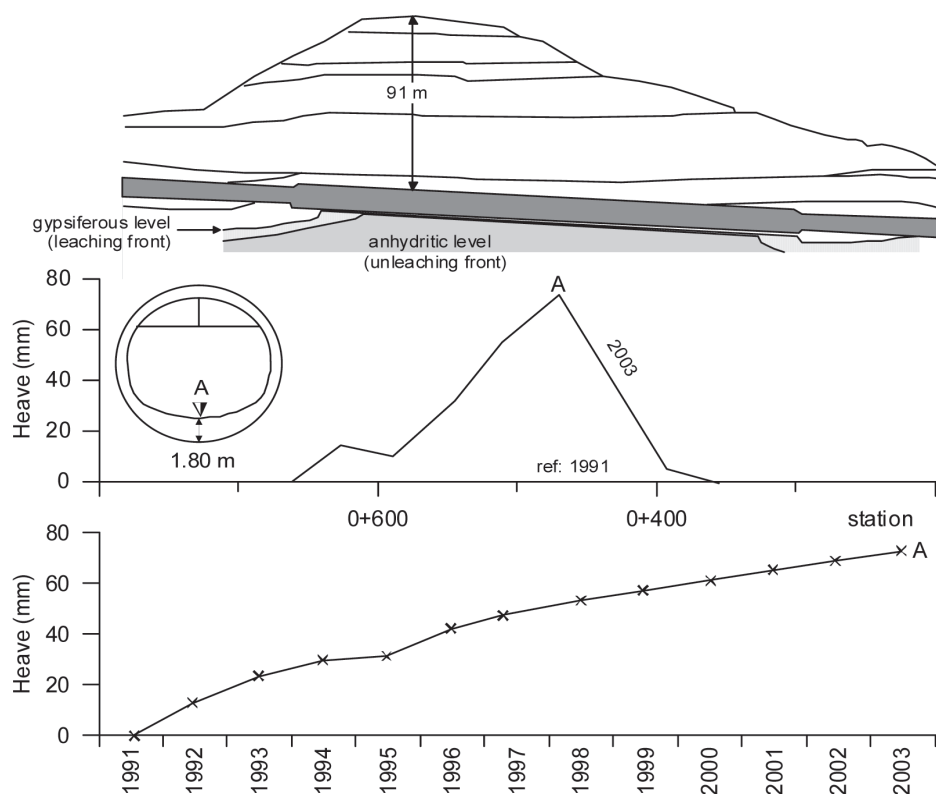


tests are presented in figure 21 a and b, respectively. An asymptotic tendency in the swelling pressure evolution was observed in this in situ test and after 385 days of monitoring a limit value of 3.2 MPa was clearly defined. Wittke (2000) pointed out that the maximum swelling pressure measured in laboratory tests amounted to approximately 6.8 MPa. A limit for heave was impossible to define in the second test even after 476 days of measurements on a swelling

block of finite dimensions. Block unloading, with fissure hydration induced swelling, could be related with the systematic increase of vertical displacements in the swelling under load test.

Wittke (2006) indicates that during construction of Heselach II expansive phenomena were not detected, in spite of the seepage of water from rainfall found in the area of the leached gypsiferous level. However,

long-term heaves without attenuation signs have been observed during operation since 1991 (see figure 22).



**Figure 22. Invert heave in Heselach II during operation (modified after Wittke, 2006).**

## CONCLUSIONS

Main general aspects regarding swelling in tunnels excavated through Triassic SBR can be summarized as follow:

- i. Expansive phenomena in SBR far exceed the expansivity threshold of most rocks and hard soils, which are well-known because of their high expansive potential (i. e. Molasse marl, Opalinus clay, Tabuk clay, Al-Qatif clay and other similar). In tunnels excavated through alternations of clayey-marly swelling rocks and SBR (i. e. Hauenstein, Bözberg and Belchen), it became clear that under similar conditions during construction and operation –particularly, under the same ventilation conditions (relative humidity,

temperature and wind velocity) both heave and swelling pressure in SBR could be up to one order in magnitude greater than in expansive clayey and marly rocks.

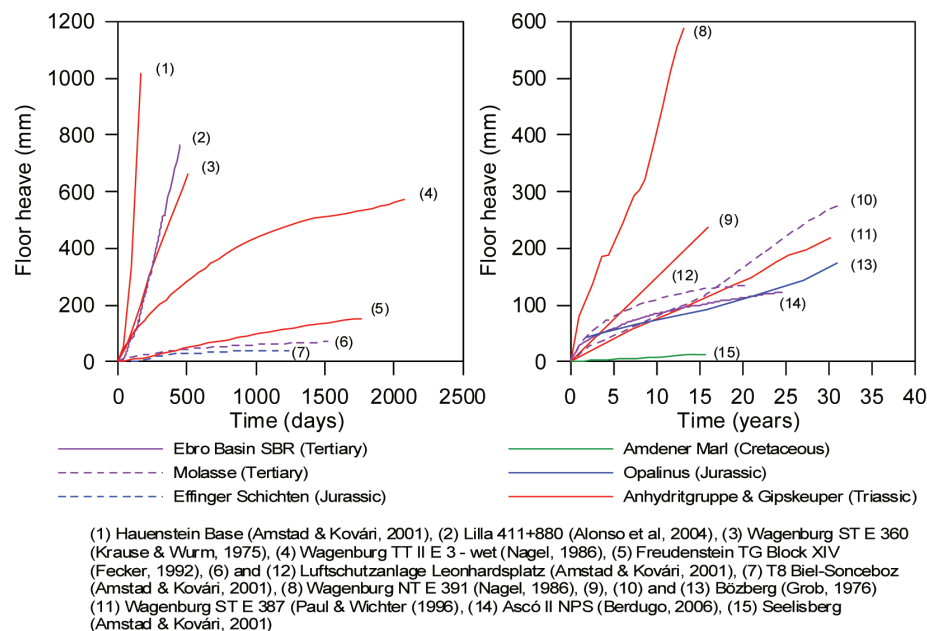
- ii. Long term observations in tunnels reveal that expansive phenomena affect exclusively the floor. Abutments and vaults remain unaffected even under strong swelling of the foundation material. This feature is unequivocally related to preferential water flow toward the bottom of excavations, where it is able to wet the material initially affected by the stress relief or evaporate due to ventilation. Then, expansion in tunnels occur preferentially in zones of water accumulation and rock weathering and not precisely in zones exposed only to water flow.
- iii. Swelling is characterized by a sudden activation

immediately after excavation, just when the rock undergone extreme changes in both confinement and suction due to the stress relief and is exposed to the environmental agents. This hypothesis is validated by the important expansive response observed after reconstruction works in the south tunnel of Wagenburg, a task that undoubtedly caused unloading and new changes in suction in the foundation material.

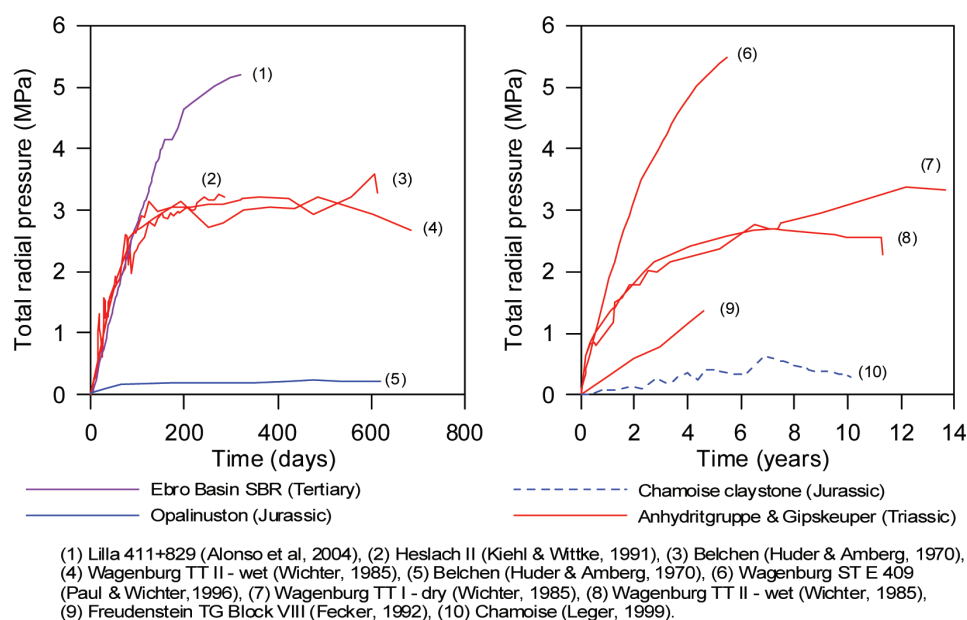
- iv. Heterogeneous distribution of swelling –particularly the distribution of swelling pressure, even in cases of homogeneous layers of SBR–, is a consequence of intrinsic heterogeneity these rocks, as well as the result of an erratic configuration of the active zone.
- v. The active zone seems to be not affected significantly by the shape of excavation and remained relatively constant since the beginning of expansive phenomena. Consequently, it is reasonable to assume that the weathering of the foundation material in tunnels excavated in SBR is also limited to a relatively well defined thickness.

- vi. After activation –and depending on support rigidity–, either heave or swelling pressures in SBR evolve at very high rates and, in some cases, an ultimate value can not be clearly defined; in contrast to some clayey rocks, characterized by asymptotic swelling–time relationships (see figures 37 and 38).
- vii. Evidences of a cause–effect relationship between self–sealing mechanisms and attenuation of either heave or swelling pressure in tunnels with resisting support are not available.
- viii. Even when important quantities of active clayey minerals are present in the host matrix of SBR (i. e. Corrensite in the Gipskeuper) –but principally in spite of the well knowledge on the asymptotic expansive behaviour of pure clayey materials–, at field scale it is difficult distinguish between the contribution of the clay expansion and the expansion due to the transformation of anhydrite into gypsum; if the latter is really possible. Then, the validity of this classic approach to interpret field swelling–time relationships in SBR is open to discussion.

relationships in SBR is open to discussion.



**Figure 37. Floor heave-time relationships in tunnels excavated through swelling rocks.**



**Figure 38. Swelling pressure-time relationships in tunnels excavated through swelling rocks**

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